THE INFLUENCE OF HIGH SPEED AIR FLOW ON THE BEHAVIOR OF ACOUSTICAL ELEMENTS

by

Clinton Earl McAuliffe

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Author

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Cambridge, Massachusetts
August , 1950

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, 39, Massachusetts

Dear Sir:

I herewith submit the attached thesis entitled THE INFLUENCE OF HIGH SPEED AIR FLOW ON THE BEHAVIOR OF ACOUSTICAL ELEMENTS in partial fulfillment of the requirements for the degree of Master of Science.

Respectfully submitted,

CLINTON EARL MC AULIFFE

ACKNOWLEDGMENTS

I wish to express my appreciation to Dr. Richard H. Bolt, thesis advisor, for his kind and constructive comments which have assisted in the preparation of this thesis. My sincere thanks go to Dr. Uno Ingård who suggested the problem and who has shown keen interest in the results of the investigation.

SUMMARY

The behavior of acoustic elements in the presence of air flow has not been studied in detail, although recent experiments with air flow have given a better understanding of non-linear acoustic resistance. The purpose of this thesis is to investigate the behavior of acoustic elements in the presence of air flow. The acoustic mass and resistance of small circular orifices are studied in detail in the presence of air flow through and past the orifice.

Although several methods of measuring acoustic impedance are available, the precision impedance tube is, perhaps, the most precise method of measuring the impedance of small orifices. Also it could be readily modified to permit air flow through the orifice. Using this method, the complex impedance of several small circular orifices for varying air flow through the orifice was measured. The resulting resistance and reactance curves obtained for several size orifices were normalized to give a single curve to represent the reactance and resistance of small orifices.

The acoustic mass of the orifice was observed to decrease rapidly over a short range of air flow to a value less than one-half the mass without air flow, and to remain constant at the reduced mass for greater air flow. The acoustic resistance changed with

increasing air flow from the usual frequency dependent radiation resistance to a constant slope resistance proportional to air flow but shown by previous investigators to be nearly independent of frequency. This change in the type of resistance occurs simultaneously with the change in mass.

Two orifices whose acoustic impedance for varying air flow had been determined by precision impedance tube measurements were used in combination with a cavity to form a resonator. The Q and the frequency of the resonator were determined for air flow through the resonator and checked against calculated values based on precision impedance measurements. In no case was the shift in frequency of the peak of the resonance curve as great as the calculated values.

A side branch resonator was used to determine the effects of air flow past an orifice. The resultant shift in frequency and lowering of the Q of the resonance curve indicates a similar change in mass and resistance.

The decrease in mass with air flow is explained as resulting from the destruction of laminar flow streamlines by turbulence. The acoustic resistance or radiation resistance, appears to experience a similar decrease, to be replaced by a different resistance independent of frequency but proportional to air flow.

I INTRODUCTION AND OBJECT

In many applications, sound waves are associated with high speed air flow, as in sirens, whistles, mufflers, ventilating systems, and industrial applications. Although considerable research has been done on acoustic elements involving a static medium, little has been done in the way of determing the effect of air flow on acoustic elements. The application of acoustic resonators in aircraft wind tunnels has shown that the resonant frequency is changed considerably by the passage of air:

Several investigators, Bolt, Labate, Ingård (5), and Sivian (15) have shown that both the reactance and resistance of orifices change for high particle velocities through the orifice caused by intense sound. It is reasonable to expect that mass and resistance of orifices may be modified by high direct current particle velocities through the orifice.

Westerfelt (21) has correlated changes of acoustic resistance resulting from air flow with non linear resistance occuring for high level sound. His results indicate that the analogous acoustic resistance, R_r defined as

$$R_r \simeq \frac{\rho \omega^2}{2\pi c}$$

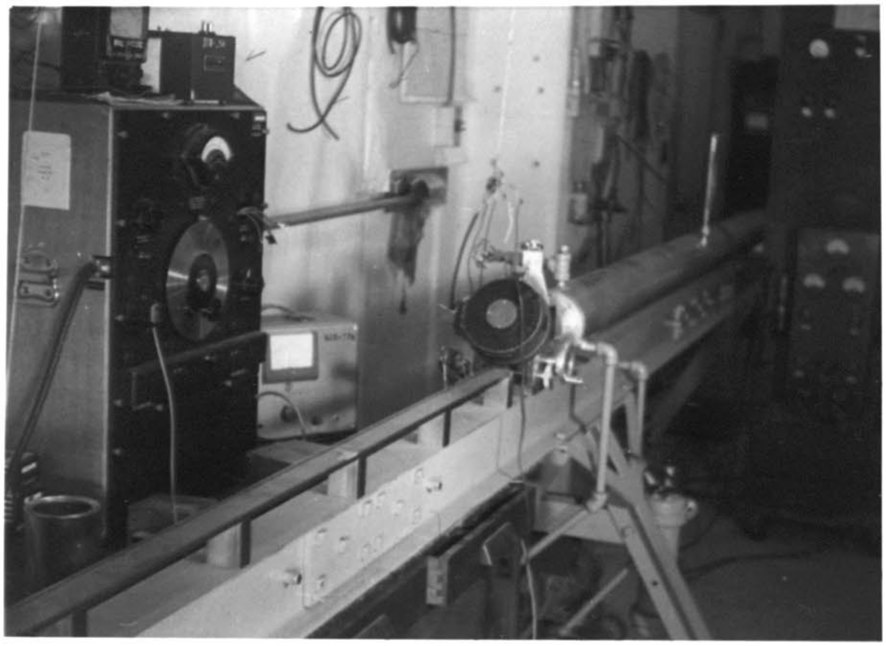
(where ρ is the density of the air; ω, the radian frequency; and c, the velocity of sound) changes to a much higher value proportional to the air flow through the orifice. The new resistance appears to be related more to hydrodynamic properties of air flow than the usual radiation impedance associated with sound being radiated from an orifice or piston.

The analogous acoustic mass defined as

$$L = \frac{\rho l_e}{S}$$

(where l_e equals the effective length of the orifice and S is the area of the orifice) includes not only the mass of the physical dimensions of the orifice but also an end correction resulting from the air on each side of the orifice contributing to the effective mass. For physically thin orifices the end correction constitutes nearly the total mass. Ingård (17) has explained the decrease of acoustic mass with high level sound as resulting from turbulence. Since turbulence is associated with direct current air flow through a constriction or orifice, similar changes of mass may be expected to take place.

The object of this thesis is to investigate the effects of air flow on acoustic elements. Measuring the impedance of orifices in the presence of air flow is one method of determining the effects. The use of a combination of orifices with a cavity enables one to determine the change of mass and resistance, but not as precisely as with an impedance tube. The effects of air flow past the orifice are determined by the use of side branch resonators.



General View of Precision Impedance Tube
FIG. 1

Flow Apparatus
FIG. 2

II PROCEDURE

A. Measurement of Acoustic Impedance

1. Precision Impedance Tube

A precision impedance tube, Beranek (22), was used to determine the complex impedance of small, circular, thin, orifices. Details of the theory used in measuring the acoustic impedance is outlined in Beranek (22) and Morse (19). In brief, the impedance of the orifice was measured by an analysis of the standing waves in a three inch tube with the orifice placed at one end and the sound source at the opposite. A traveling microphone in the tube was used to locate the points of minimum sound pressure, and to determine the sound pressure levels of the maximum and minimum points. From the knowledge of the standing wave ratio; ie, ratio of minimum to maximum sound pressure and the distance of the first pressure minimum from the orifice, it is possible to determine the complex impedance ratio by entering charts of the complex hyperbolic tangent mapped on the U-V plane.

2. Flow Measuring Apparatus

The usual impedance tube was modified to permit air flow to be introduced in one end, pass through the orifice, and exhaust through an absorbing wedge at the other end. The rate of air flow through the orifice was determined by measuring the volume of air flow by a precision flow meter, and converting the volume flow rate to linear flow rate by dividing by the cross section of the orifice. A general view of the meter is shown in Figure 2. Reasonable accuracy from the wet test meter required that the volume flow be less than 250 cubic centimeters per second.

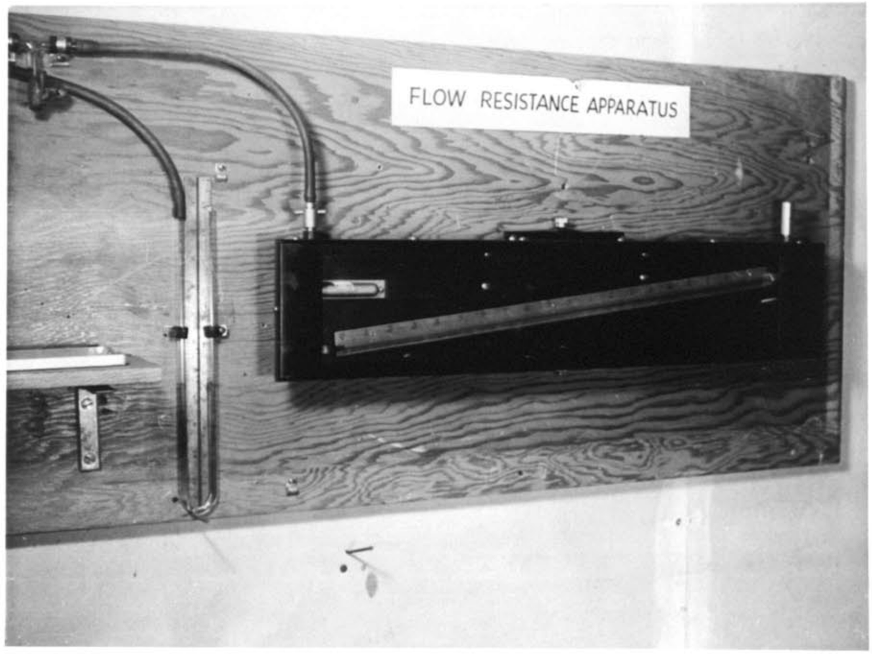
The true linear velocity of the air through the orifice is difficult to determine, although the accuracy with which the volume flow was measured introduced little error. The true linear velocity is given by dividing the volume velocity by the effective area of the orifice. This area is a function of the tube diameter, the orifice diameter, and Reynolds number. Reynolds number is a function of the velocity of flow in the tube, therefore, with fixed tube and orifice dimensions, the effective area varies with the velocity of air flow. Hunsaker and Rightmire (20) present empirical curves showing the effective diameter of an orifice as a function of Reynolds number. Although these curves do not extend to Reynolds numbers as low as used in these experiments (below 300 centimeters per second) a rough extrapolation of the curve shows an effective diameter of .6 or .7 of the measured physical diameter for the size of the orifices used. At these low Reynolds numbers the effective diameter changes slightly so that the rate of flow obtained by dividing the volume flow by the cross sectional area will not give a perfectly linear scale, but over a short range, this variation will be only slight. The scale for linear flow rates should be slightly compressed for low flow rates, but should be perfectly linear above about 1000 cm/sec.

3. Choice of Orifice Dimensions

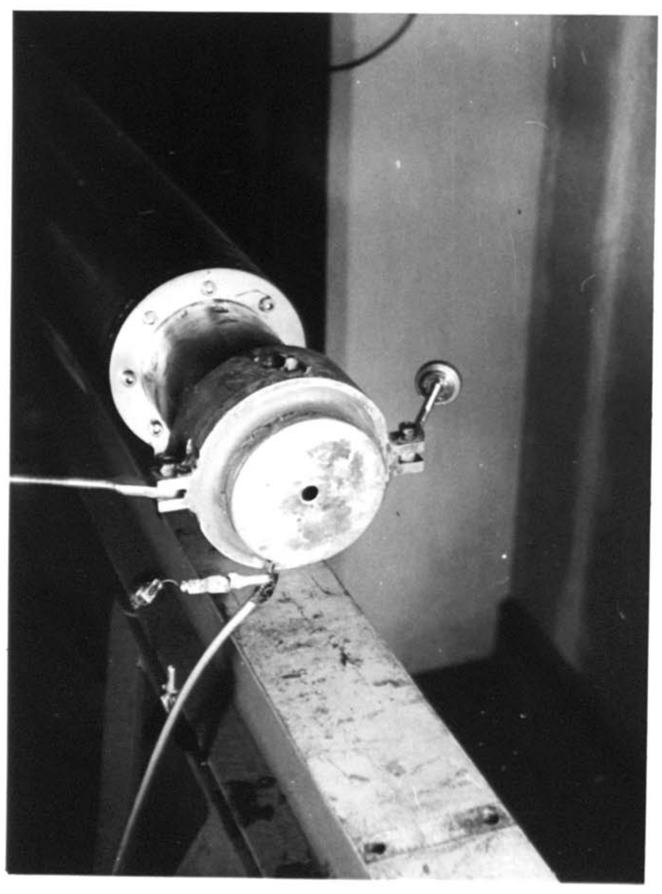
Only physically thin orifices were chosen for study, all being 0.0508 centimeters thick at the orifice but tapering from the circumference. Thin orifices were chosen because the acoustic mass consisted principally of the end correction, and the resistance principally of radiation resistance. The diameter of the orifices studied was limited by the capacity of the wet test meter, since volume flows of less than 300 cubic centimeters per second were the maximum that could be measured. This limitation required that the largest orifice which would show appreciable change of impedance was the 1 centimeter diameter orifice.

4. Intensity of Sound Used in Experiments

Sound pressure levels of about 80 decibels were used in all measurements in order to avoid the complications caused by the non-linearity of high level sound. This sound pressure level resulted in particle velocities in the orifice well within the linear region, and only a small fraction of the direct current particle velocities developed by air flow.



Water Manometer
FIG. 3



Orifice mounted in Impedance Tube
FIG. 4

5. Procedure in Making Impedance Measurements

For each orifice, the procedure consisted in making the usual impedance measurements with the precision impedance tube, with the added condition of air flow through the orifice. Each impedance measurement was made twice and the results averaged to obtain each plotted point on the impedance graphs, Figure 9, 10 and 11. While impedance measurements were being made, the time for three liters to flow was clocked and recorded. Since the pressure variation in the compressor system resulted in cyclic variations, it was necessary to take several readings and average the results, while carrying out impedance measurements for a given rate of flow. Although considerable variation in air flow occurred, which resulted necessarily in considerable change in impedance of the orifice while measurements were being made, the results obtained gave consistent and smooth curves over most of the range of flows studied.

6. Impedance Measured with Air Flow in Both Directions

Air flow was reversed for the 0.5 centimeter diameter orifice to determine if the impedance of an orifice is dependent upon direction of flow. Since measurements showed no dependence on direction of flow, for this particular orifice, other measurements were made without regard to direction of air flow.

7. Resistance of Orifice Determined by Pressure Gradient

The flow resistance R_f, defined as the ratio difference in the ~~of the~~ pressure ~~gradient~~ on each side of the orifice to the volume flow was determined by using the flow meter in conjunction with a water manometer, Figure 3. The plot of pressure versus linear velocity results in a parabola, as shown in Figure 17.

B. Effect of Air Flow on Resonance

Two acoustic resonators were used to determine the effect of air flow on resonance. The first consisted of a cavity of volume 173.6 cubic centimeters, and two orifices, one of 0.357 and 0.5 cm diameter orifice. This combination gave a peak resonance frequency of 303 cycles per second and a Q of 5.44. For a given air flow, the sound pressure level in front of the cavity was kept constant, and the pressure inside the cavity was measured at near resonant frequencies. Air velocities through the cavity were great enough to cause both orifices to undergo a change in mass and resistance simultaneously. The resulting resonance curves are shown in Figure 14. Increasing air flow caused a decrease in Q and a shift in the peak frequency.

The second cavity was a 1000 cubic centimeter volume, used in combination with 1.4 and 0.5 centimeter diameter orifices. From previous impedance measurements,

Small Cavity, one Orifice
FIG. 5

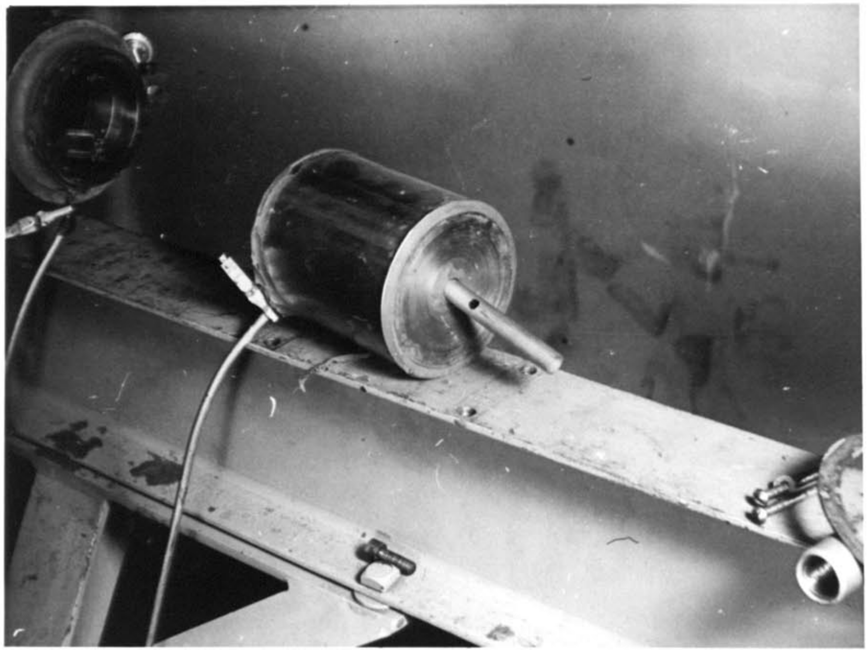
Large Cavity
FIG. 6

it was known that air velocities through the 1.4 centimeter diameter orifice would not be great enough to cause any appreciable change in impedance. The resonance curves obtained in Figure 15 reflect the changes which occur as a result of air flow through the 0.5 centimeter diameter orifice. It will be noted that with increasing air flow, the Q of the combination decreases and the frequency increases until a certain flow rate is reached at which time the frequency decreased with increasing air flow and the Q of the combination increases. For high rates of air flow, the peak frequency is below the original frequency of the combination with no air flow.

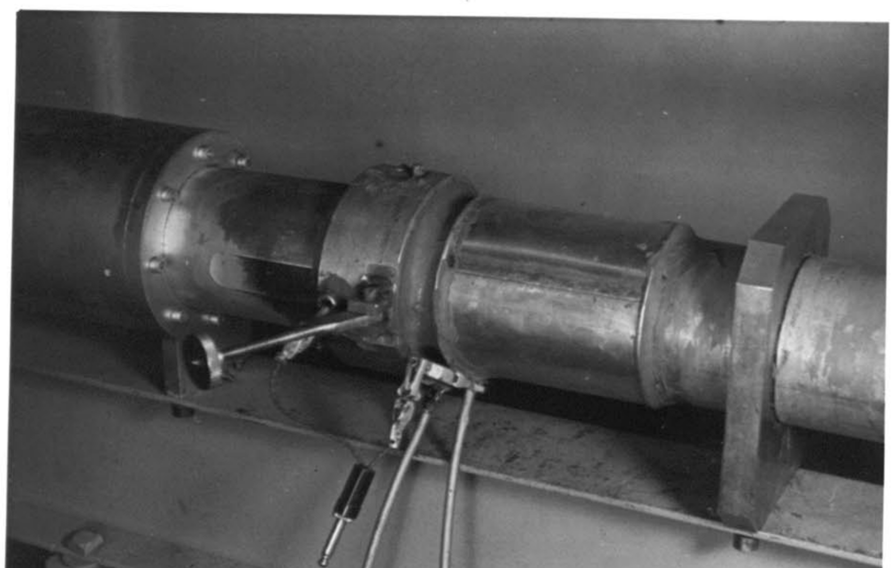
For the two resonators considered, the two orifices used with the cavity, were used singly with the cavity to determine the peak frequency of a simple Helmholtz resonator. Using the value of the mass as measured by the impedance tube, the shift in frequency of the combination was computed and checked against the resonant curve obtained for the combination with no air flow. The results were in excellent agreement as shown in Tables 1 and 2.

C. <u>Determining Effect of Air Flow past an Orifice</u>

A side branch resonator was used to determine the effect of air flow past an orifice. Here again, the necessity of obtaining great enough air velocities to cause appreciable change in the orifice mass and



Side Branch Resonator (Inner Tube partially removed to show Orifices)
FIG. 7



Side Branch Resonator Mounted on Impedance Tube with Absorption Wedge on Opposite End.
FIG. 8

resistance required that a small diameter tube be used. The side branch resonator constructed consisted of a 1000 centimeter cavity, through which a 1.27 centimeter (outside diameter) tube was placed. The inside diameter of the tube was 0.636 centimeters thus providing particle velocities above 1000 centimeters per second. Two holes of 0.541 centimeter diameter were drilled in the center of the tube as shown in Figure 7. A 640AA condenser microphone with a probe was used to measure the sound pressure level at the location of the two orifices in the tube. The probe was inserted perpendicularly to the tube through the cavity and into the tube to be flush with the inner wall of the tube midway between the 2 holes drilled from opposite sides through the tube. The combination of 2 orifices and cavity resulted in a resonant peak of 140 cycles per second and having a measured Q of 2.8. Although the Q was not great because of the thickness of the tube walls, the inherent difficulties of mounting the probe and microphone on the impedance tube were simplified by the use of the thicker tube walls. Resonance curves were obtained for several velocities of air flow through the tube past the orifices. Shift in frequency and lowering of Q occurred just as with the case of air flowing through the orifice.

III RESULTS

A. Orifice Impedance by Precision Impedance Tube Measurements.

The results of the measurement of impedance of the 0.357, 0.5 and 1 centimeter diameter orifices are shown graphically in Figures 9, 10, 11, and 12. It will be noticed that all orifices studied appear to undergo the same change in mass and resistance with air flow. To determine if one curve can be used to represent this general change, all reactance and resistance curves were normalized in Figure 12. The reactance and resistance when multiplied by the effective area of the orifice and plotted against linear flow rates, yield the same curve, with slight variation for the 1 centimeter diameter curve.

The linear flow plotted is obtained merely by dividing the volume flow by the area of the orifice, thus not giving the true particle velocity through the orifice. The particle velocity is approximately 1.6 times the values shown for the two smaller orifices. For the larger orifice, the value would be in the vicinity of 1.8 times the flow indicated at low flow rates and decreasing to a value of 1.65 for higher flow rates where the effective area becomes independent of velocity. This probably indicates why the 3 normalized curves do not entirely agree. It is interesting to note that the same normalizing factor which normalizes the mass likewise normalizes the non-linear resistance.

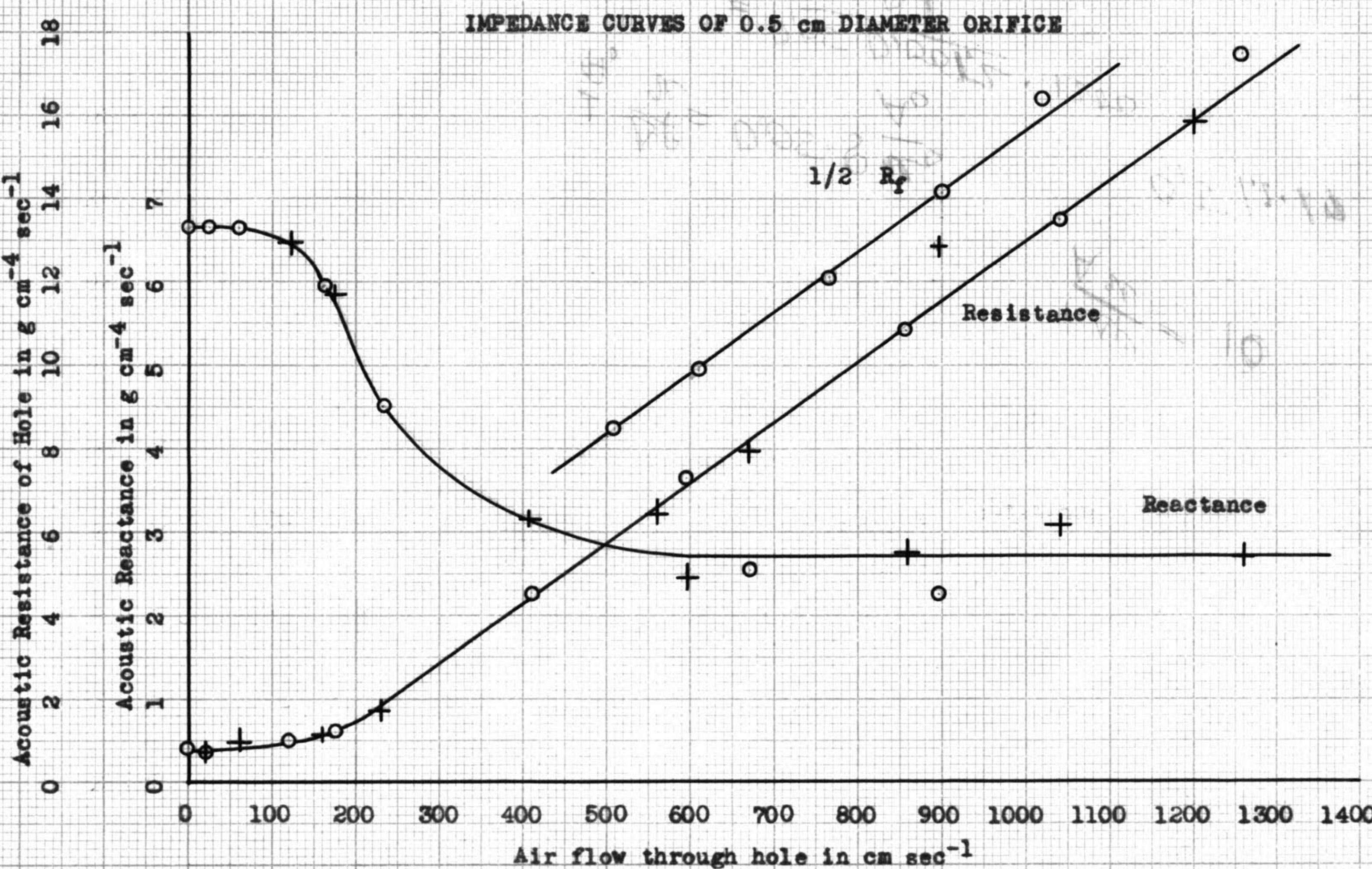

IMPEDANCE CURVES OF 0.5 cm DIAMETER ORIFICE
1/2 R_f
Resistance
Reactance
Acoustic Resistance of Hole in g cm^{-4} sec^{-1}
Acoustic Reactance in g cm^{-4} sec^{-1}
Air flow through hole in cm sec^{-1}
0 2 4 6 8 10 12 14 16 18
0 1 2 3 4 5 6 7
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400

FIG. 9

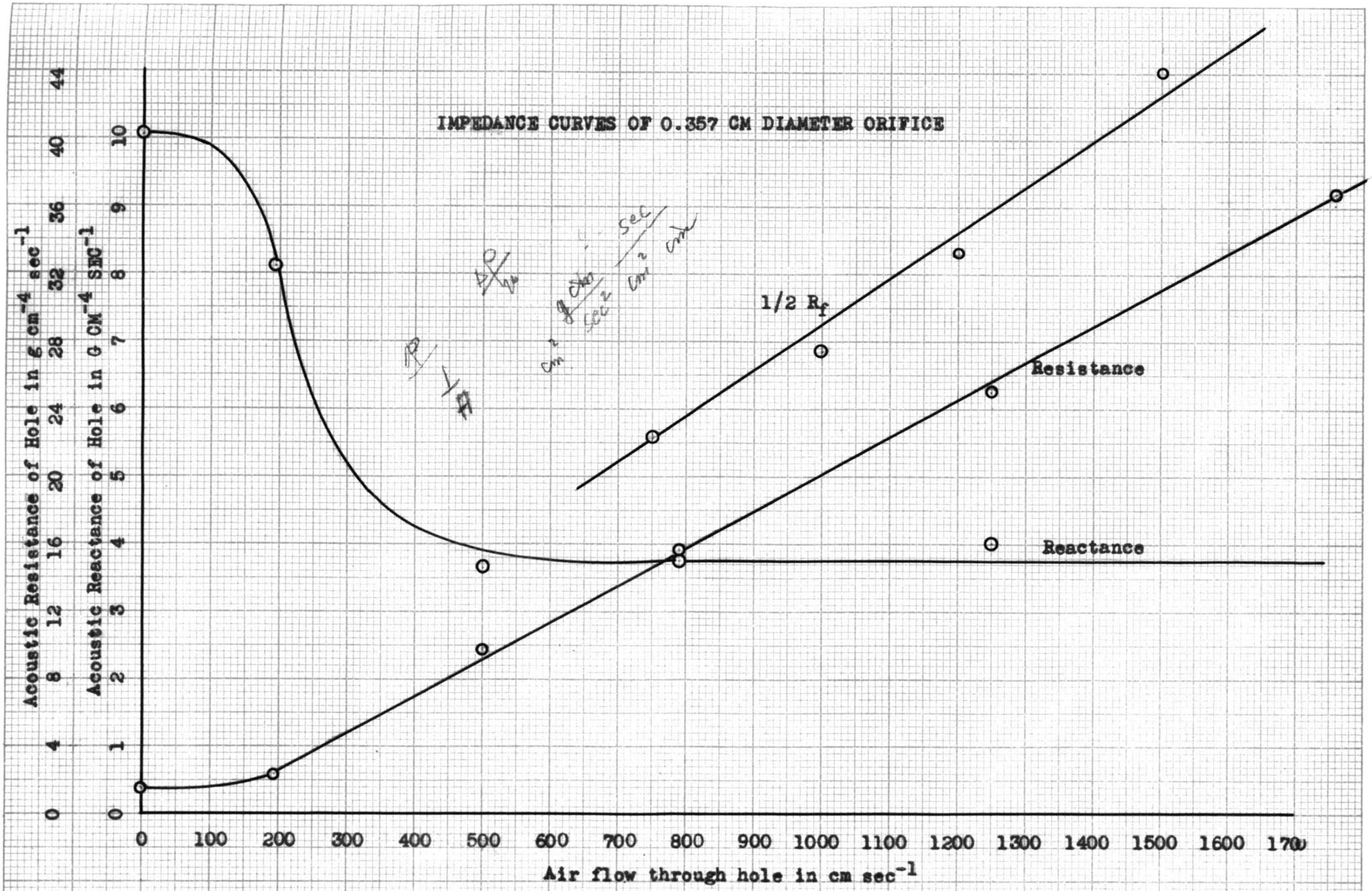

IMPEDANCE CURVES OF 0.357 CM DIAMETER ORIFICE
Acoustic Resistance of Hole in g cm^{-4} sec^{-1}
Acoustic Reactance of Hole in G CM^{-4} SEC^{-1}
Air flow through hole in cm sec^{-1}
1/2 R_f
Resistance
Reactance
0
4
8
12
16
20
24
28
32
36
40
44
0
1
2
3
4
5
6
7
8
9
10
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700

FIG. 10

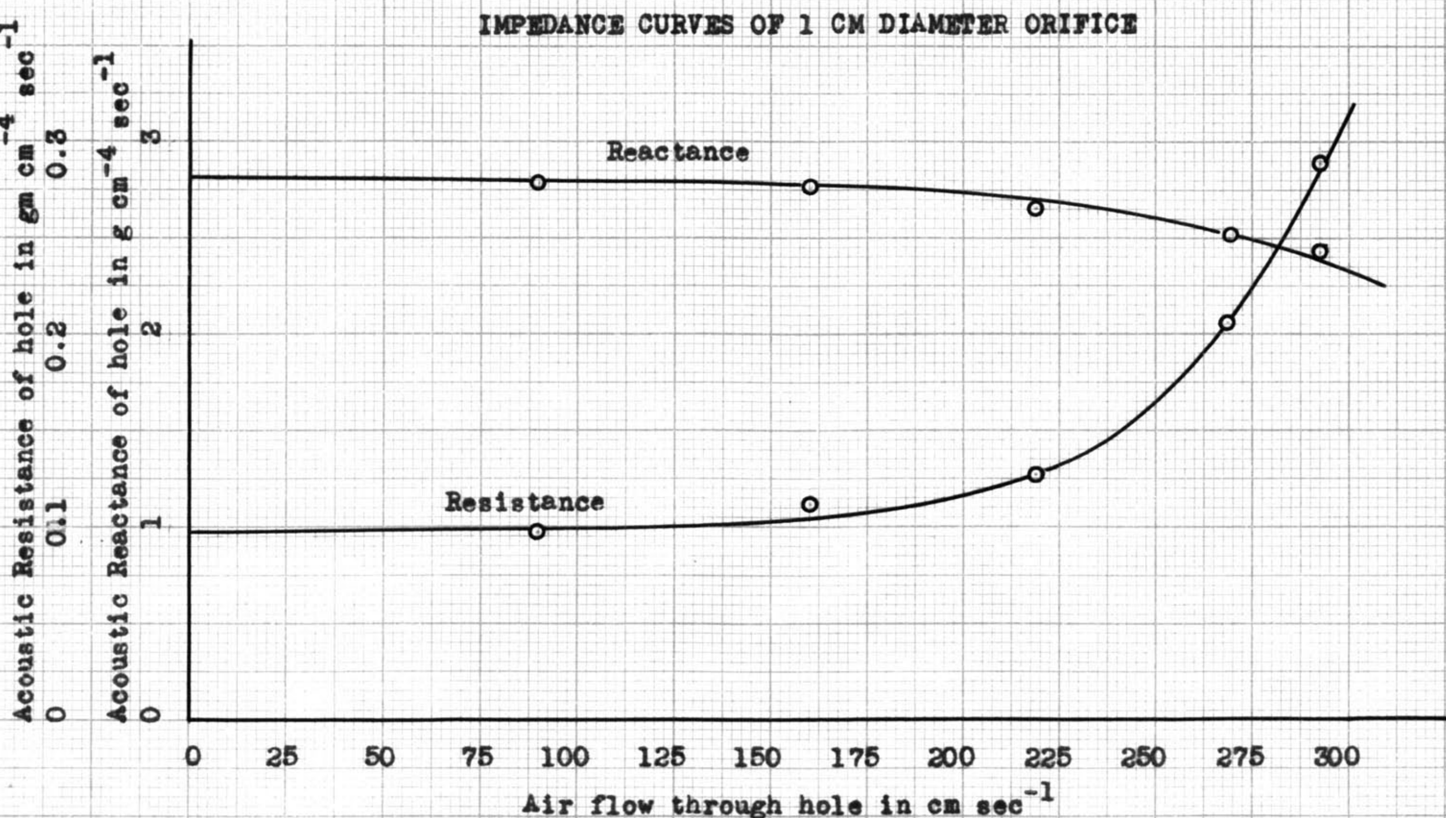

IMPEDANCE CURVES OF 1 CM DIAMETER ORIFICE
Reactance
Resistance
Acoustic Resistance of hole in gm cm^{-4} sec^{-1}
0
0.1
0.2
0.3
Acoustic Reactance of hole in g cm^{-4} sec^{-1}
0
1
2
3
0
25
50
75
100
125
150
175
200
225
250
275
300
Air flow through hole in cm sec^{-1}

FIG. 11

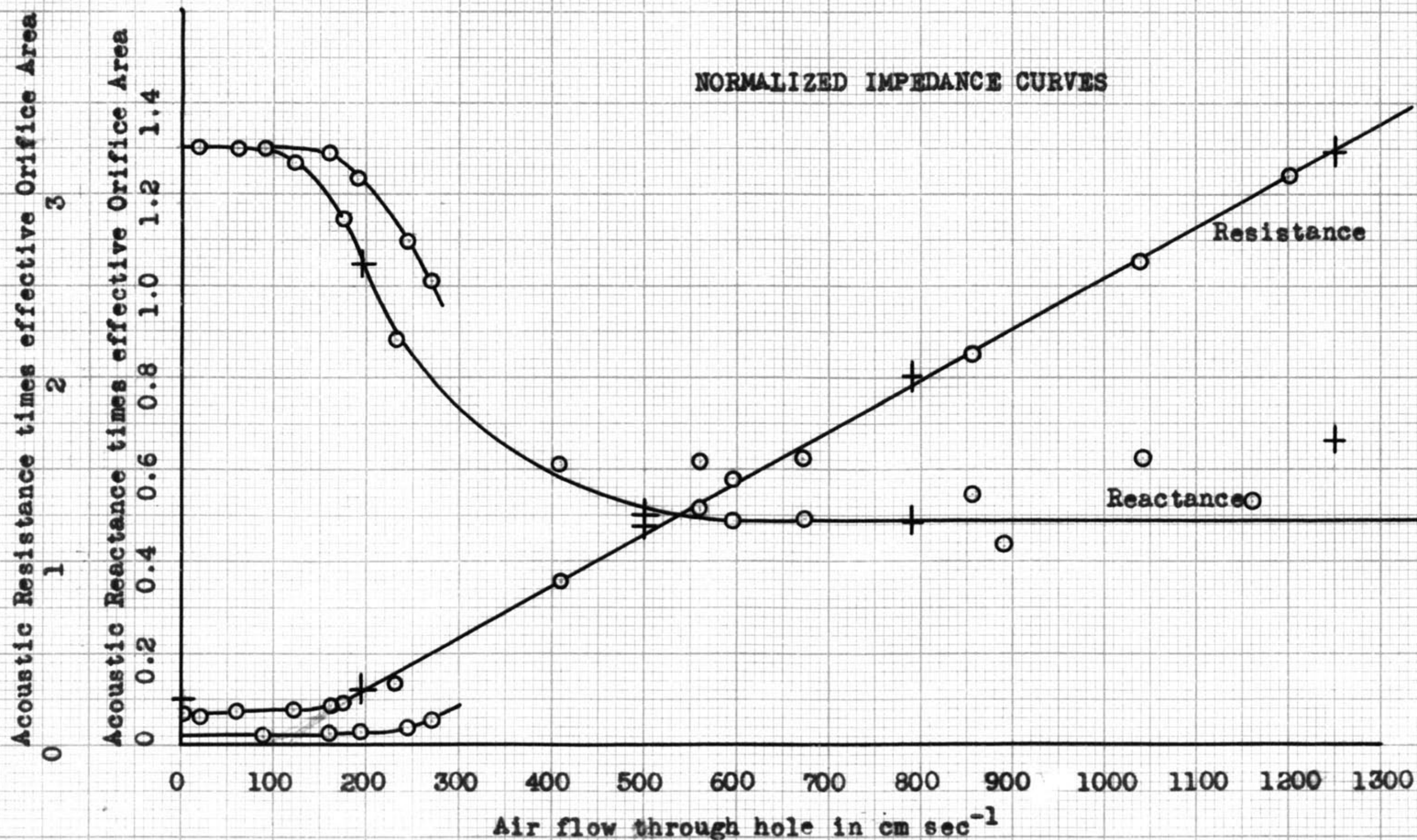

NORMALIZED IMPEDANCE CURVES
Resistance
Reactance
Acoustic Resistance times effective Orifice Area
Acoustic Reactance times effective Orifice Area
0
1
2
3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
Air flow through hole in cm sec^{-1}

FIG. 12

1. Independence of Direction of Air Flow

The Acoustic reactance and resistance of an orifice is independent of the direction of air flow. Figure 9 shows the resulting measured reactance and resistance of the 0.5 centimeter diameter orifice for air flow through the orifice in the direction of the incident sound and for air flow through the orifice against the incident sound. There is close agreement between the points on the curve obtained for the two directions of air flow, thus indicating that the acoustic mass and resistance of an orifice are independent of direction of air flow.

2. Rectilinearity of the Non-Linear Resistance Curve

The Acoustic resistance of an orifice with air flow greater than 300 cm per second has a straight line relationship. The slope of the non-linear resistance is determined by the effective diameter of the orifice. Westerfelt (21) has shown that this resistance is comparatively constant with frequency. The curved part of the resistance curve on the other hand represents a combination of the usual radiation resistance which varies with frequency and the non-linear resistance which Westerfelt has named differential resistance.

3. Change of Mass of an Orifice with Air Flow

The acoustic mass or reactance of an orifice decreases sharply with air flow over a very short range of values, and then remains reasonable constant at higher rates of flow. Figures 9 and 10 show graphically this change in mass which occurs with air flow. The sharp decline in the acoustic mass occurs during the same flow rates as when the acoustic resistance is changing slope rapidly from the linear region to the non-linear constant slope resistance, thus indicating the same physical change associated with air flow is responsible for the change in mass and resistance.

4. Normalized Impedance Curves

The impedance curves of Figure 9, 10 and 11, for several size orifices can be normalized to a single curve by multiplying the acoustic resistance or reactance by the effective diameter of the orifice. The normalized curves are shown in Figure 12. The abscissa is the linear flow rate obtained by dividing the volume of air flow by the physical area of each orifice. At low Reynolds numbers, the ratio of the effective area to the physical area of the larger orifice is greater than for the smaller orifices, thus if the acoustic impedance multiplied by the effective orifice area were plotted against true velocity of air flow, one should expect a single reactance curve and resistance curve in the non-linear region.

5. Flow Resistance

The flow resistance R_f determined by measuring the pressure gradient on each side of the orifice for a given flow has been defined as p/vS for a given orifice, where v is the particle velocity and S the area of the orifice. Westerfelt (22) has shown $R_f/2$ to be equal to R_d, the differential acoustic resistance. Neglecting frictional losses, then, the curve $R_f/2$ versus air flow velocity should be identical with the curve for the acoustic resistance at high rates of air flow shown in Figures 9 and 10. The curves correspond very well for the 0.5 cm diameter orifice, but for the 0.357 cm diameter orifice, the curve for $R_f/2$ is displaced upwards though of about the same slope.

6. Comparison of Acoustic Impedance for High Level Sound with Acoustic Impedance for Air Flow

The Acoustic reactance and resistance of an orifice changes with air flow in a manner somewhat similar to high alternating particle velocities, if one may judge from the shape of the curves obtained for each. Figure 13 shows the acoustic impedance plotted against the root mean square particle velocity for high level sound and for air flow. The high level sound curves are 200 cps and were taken from a paper by Bolt, Labate and Ingård (5). A similarity between the curves exists, although there is no exact correspondence.

B. Acoustic Resonators in the Presence of Air Flow Through the Orifices

Air flow through acoustic resonators composed of a cavity and two orifices, both of which are effected by

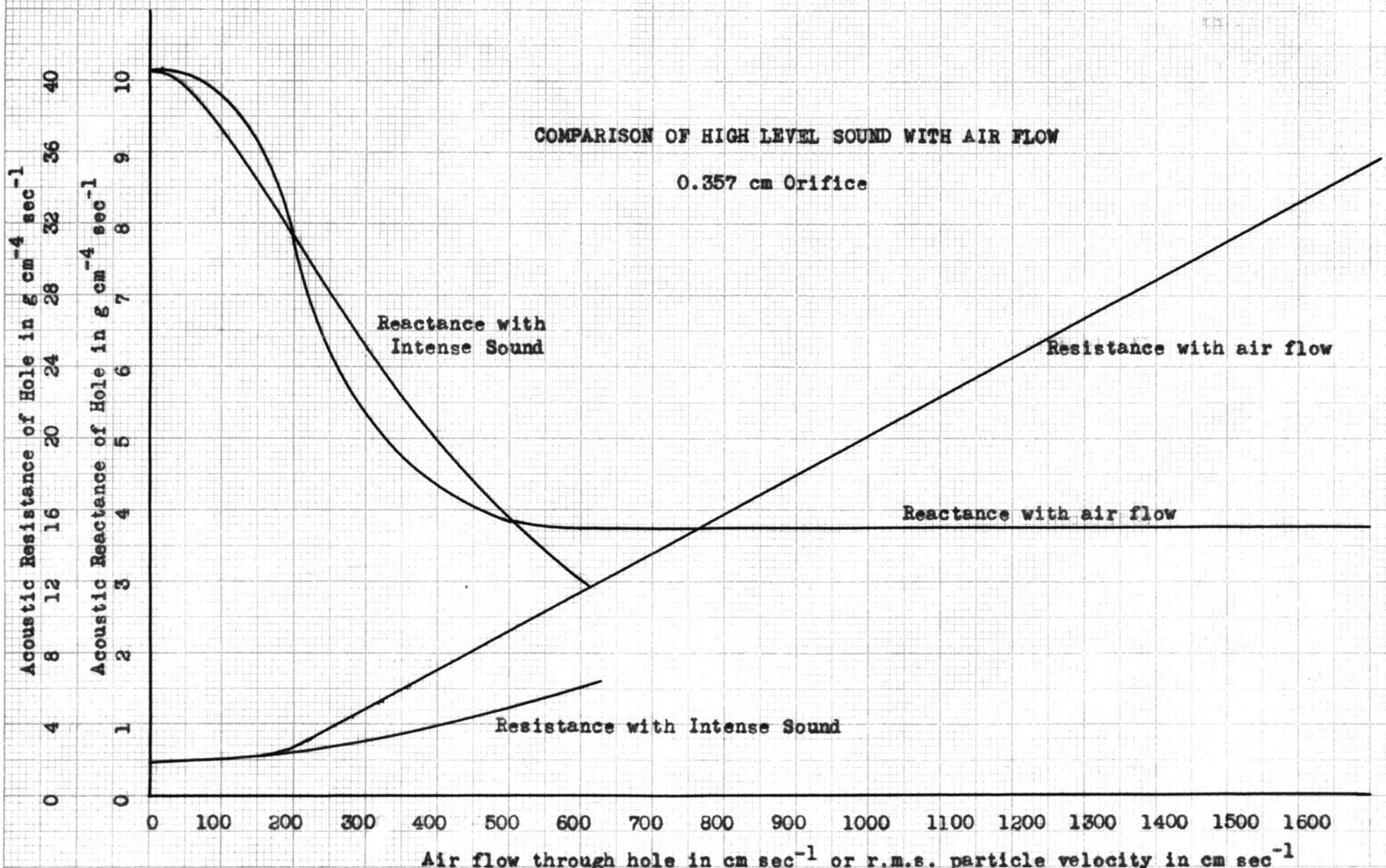
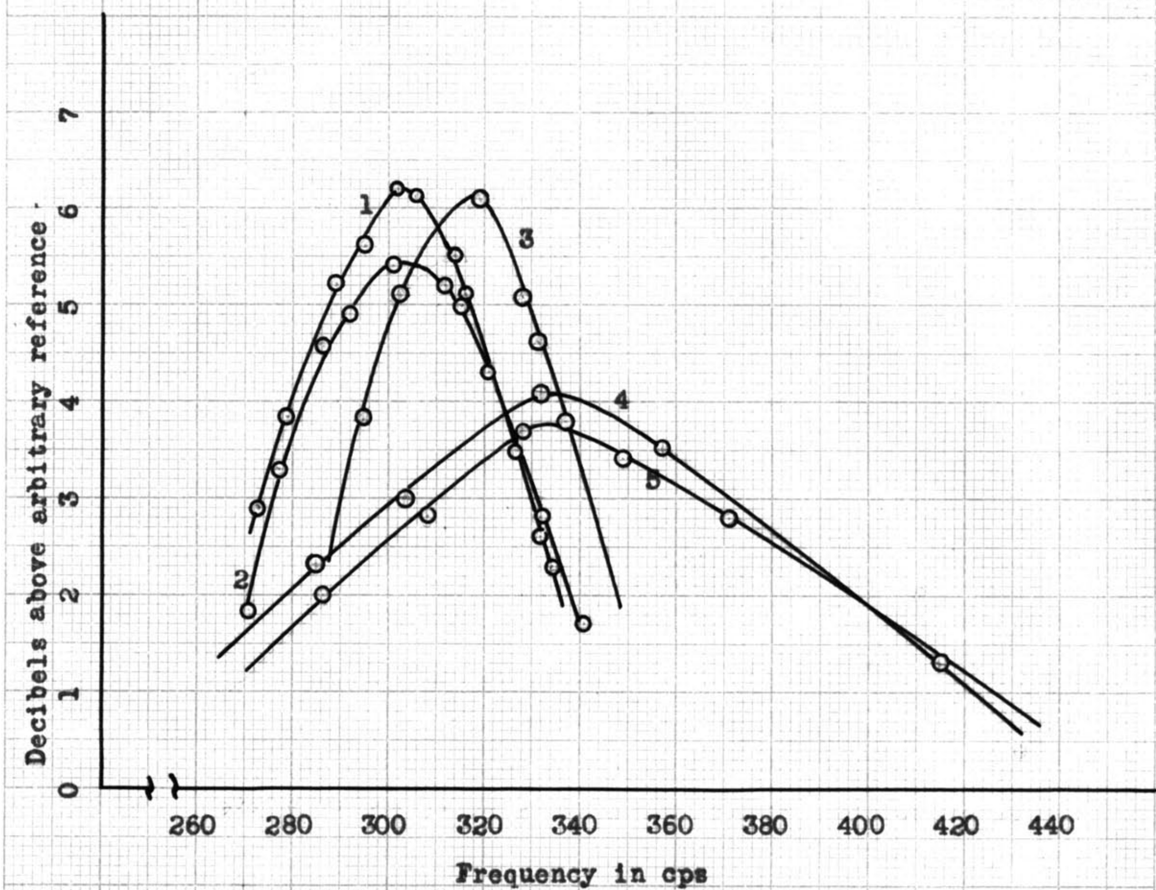

COMPARISON OF HIGH LEVEL SOUND WITH AIR FLOW
0.357 cm Orifice
Acoustic Resistance of Hole in g cm^{-4} sec^{-1}
Acoustic Reactance of Hole in g cm^{-4} sec^{-1}
Reactance with Intense Sound
Resistance with air flow
Reactance with air flow
Resistance with Intense Sound
0 4 8 12 16 20 24 28 32 36 40
0 1 2 3 4 5 6 7 8 9 10
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600
Air flow through hole in cm sec^{-1} or r.m.s. particle velocity in cm sec^{-1}

FIG. 13

air flow, results in a shift in the frequency of the peak to a higher frequency and a broadening of the resonance curve with increased frequency. Figure 14 is a graph of the resonance response of a cavity of volume 173.6 cubic centimeters, with a 0.5 cm diameter orifice on one end and a 0.357 diameter orifice on the opposite. Table I is a tabulation of computed resonance frequencies for the combination taken from the reactance curves determined by impedance tube measurements, Figures 9 and 10. Also tabulated are the actual peak frequencies of resonance curves obtained by experiment. In all cases it will be observed that the resonant peak is lower in frequency than the computed frequencies. The broadening of the resonance curve with increasing air flow is caused by the increased resistance due to air flow and checks roughly the resistance obtained by impedance tube measurements. Close agreement between values of resistance obtained by resonance curves measurements and impedance tube measurements is not expected because of the variation in the acoustic resistance with frequency when no air flow is present or when the resistance is changing to the differential resistance.

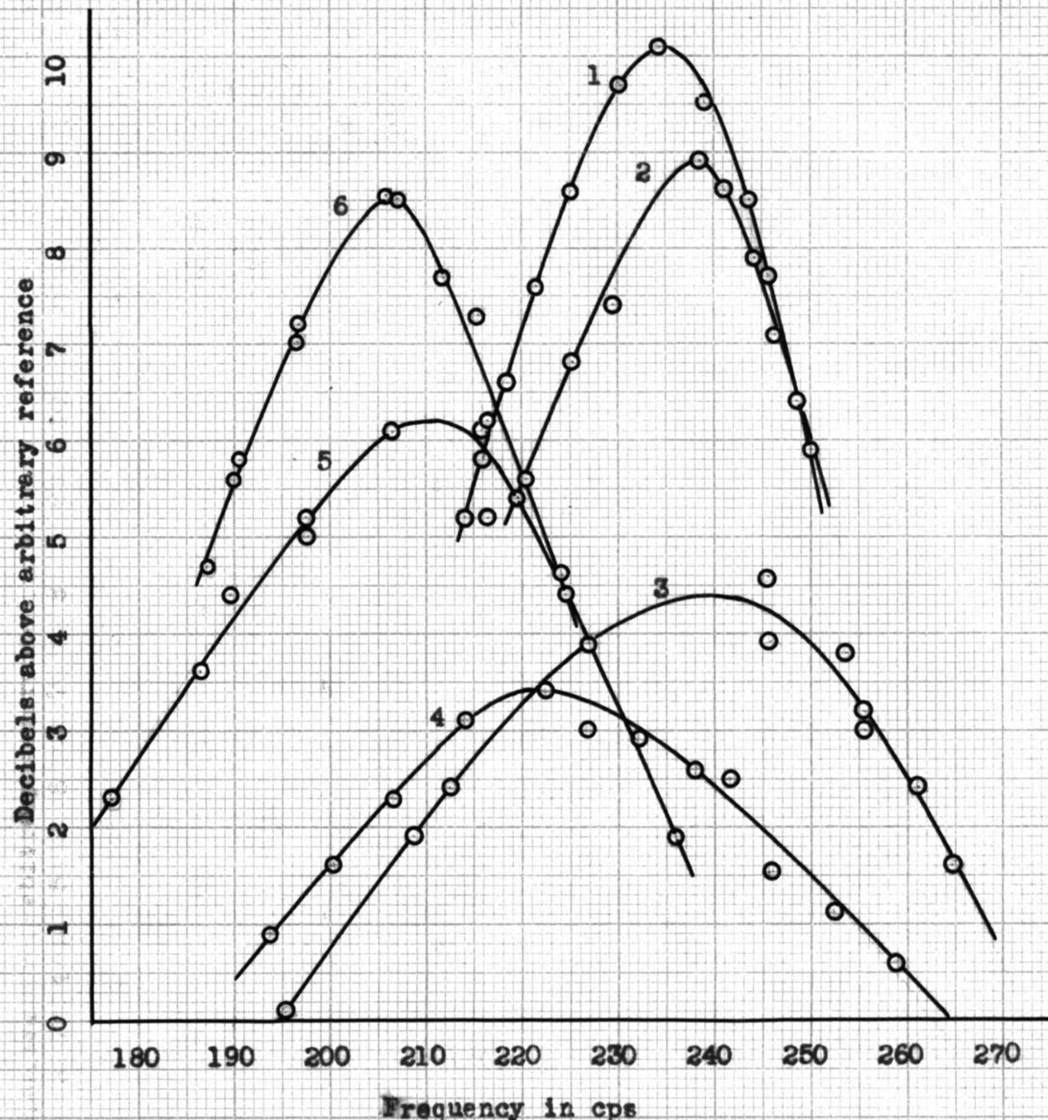
An Acoustic resonator composed of one orifice which undergoes a change of mass and resistance with air flow and a second orifice of dimensions great enough that no change in impedance occurs within the rate of



RESONANCE CURVES, SMALL CAVITY
0.357 cm and 0.5 cm diameter
orifices with flow through cavity

	Volume Velocity
Curve 1	0
Curve 2	5.3
Curve 3	26.3
Curve 4	35.3
Curve 5	70.0

FIG. 14



RESONANCE CURVES, LARGE CAVITY
0.50 cm and 1.4 cm diameter
orifices with flow through cavity

	Volume Velocity
Curve 1	0
Curve 2	17.5
Curve 3	31.9
Curve 4	49.2
Curve 5	79.0
Curve 6	181.8

FIG. 15

TABLE I

Comparison of Resonance Frequency for the small cavity with computed frequency.

Volume Flow in cm^3/ sec.	Equivalent mass of Two Orifices in g/cm^4	Computed Ratio of Resonant Frequency with Air Flow to Frequency of No Flow	Observed Ratio of Resonant Frequency to Freq. of No Flow	Observed Q
0	1.595×10^{-3}			5.44
5.3	1.59×10^{-3}	1.002	1.0	4.82
26.3	1.21×10^{-3}	1.147	1.05	6.36
35.3	1.004×10^{-3}	1.26	1.11	2.22
70.0	$.716 \times 10^{-3}$	1.491	1.19	2.4

TABLE II

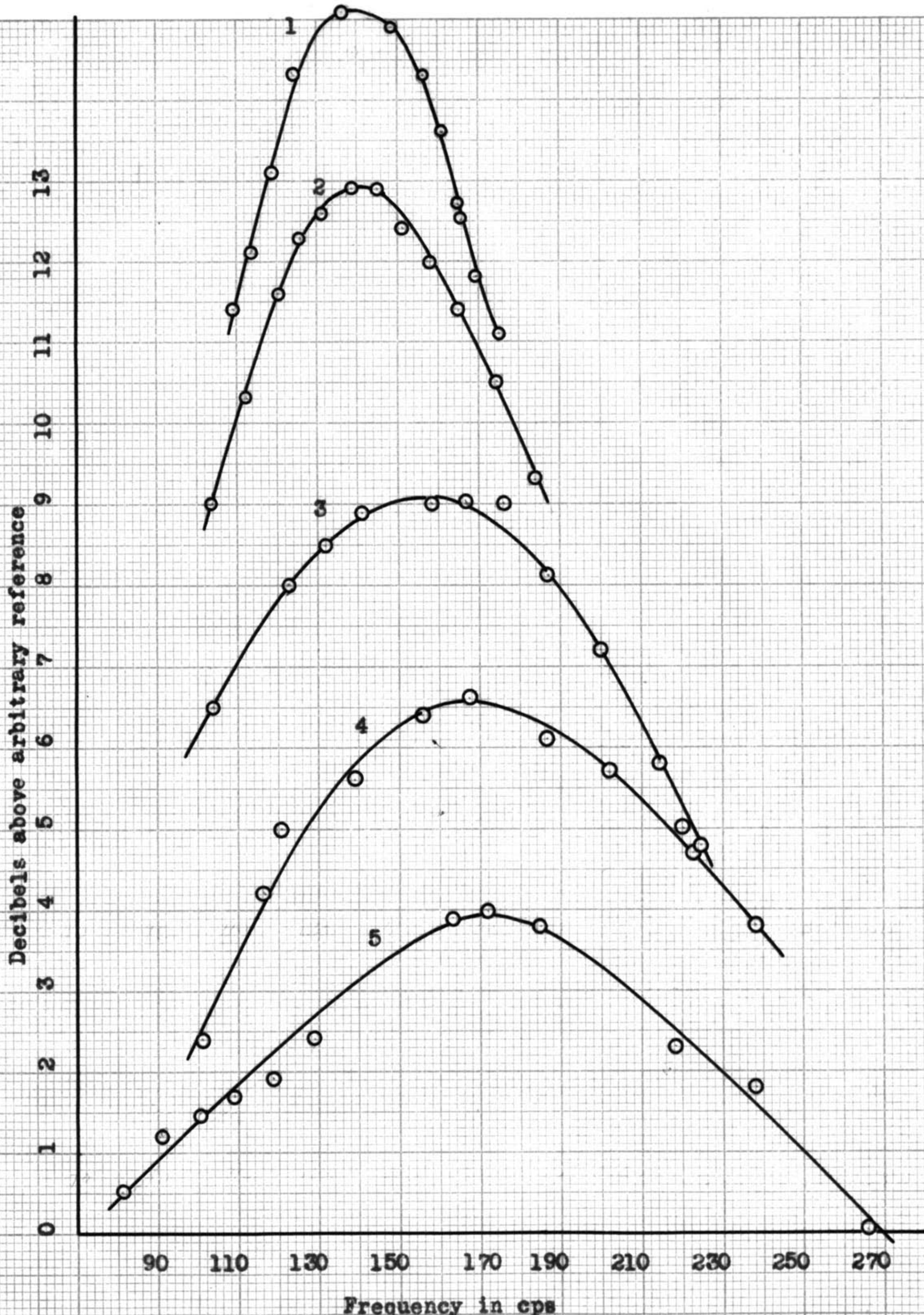
Tabulation of Frequency and Q of large Resonator with Air Flow (one orifice undergoing mass and resistance change)

Volume Flow in cm^3/sec.	Peak Frequency in cps.	Q of Combination
0	234	8.67
9.31	235	8.7
17.5	238	7.44
32.3	236	3.75
79.0	210	4.34
182.0	207	5.74

air flow, results in quite different effects with increasing air flow. The first effects are a shift in frequency to higher values and a broadening of the impedance curve as the flow rate is increased until the mass of the orifice reaches its constant value. Increased air flow beyond this value (namely, about 400 centimeters per second) has the effect of increasing the acoustic resistance of the orifice. Increasing the acoustic resistance further has the effect of closing the orifice and the resultant resonance curve decreased in frequency as air flow is increased. Also the Q increased with greater air flow. The frequency shift down is very pronounced and approaches the resonant frequency of the cavity and one orifice unaffected by air flow. This change is shown in Figure 15, the curves being numbered in chronological order of increasing air flow.

C. Changes of Acoustic Mass and Resistance of an Orifice with Air Flow Past the Orifice

The Acoustic resistance and reactance of an orifice undergoes a similar change when air flow is past the orifice in lieu of flow through the orifice. Figure 16, the resonance curves of a side branch resonator consisting of a 0.636 centimeter diameter tube with two orifices opening into a cavity, shows how the frequency increases with air flow and how the Q is lowered. The



RESONANCE CURVES WITH AIR FLOW
PAST ORIFICES

	Linear Velocity
Curve 1	0
Curve 2	140
Curve 3	266
Curve 4	378
Curve 5	450

FIG. 16

TABLE III

Resonance Frequency of Side Board Resonator with Air Flow Past Orifice

Linear Velocity in cm/sec.	Peak Frequency in cps.	Q of Combination
0	140	2.8
140	140	1.98
266	156	1.43
378	170	1.36
450	173	1.115

slender tube through the cavity permitted measurement of resonance curves for flow velocities past the orifices as great as 450 cm per second. For the highest flow rate used, the frequency shifted from 140 cycles per second to 173 cycles per second and the Q lowered from 2.8 to 1.115. Table III is a tabulation of peak frequencies and Q of the resonator versus velocity air flow past the orifices.

IV DISCUSSION OF RESULTS

A. Impedance of Orifice with Air Flow Through the Orifice

1. Physical Reasons for the Observed Change of Mass or Reactance of Orifice.

The acoustic mass of an orifice consists of the mass of the orifice plus the mass contributed by the end corrections. For sound below 1000 cycles per second, this mass may be considered as concentrated in the vicinity of the orifice. In steady state oscillation, we should find the molecules of the gas vibrating back and forth, neglecting random motion. The paths of vibration may be regarded as streamlines. These streamlines are parallel and concentrated at the center of the orifice, but in the presence of a static medium, diverge on both sides of the orifice. Thus, it is seen that for low oscillating particle velocities, the molecules oscillate along their streamlines in true laminar fashion.

Air flow passing through the orifice modifies the smooth laminar flow that occurs for low level sound. For very low rates of air flow, the streamlines through the orifice persist and the flow remains laminar. Then, as the flow is increased and turbulence sets in destroying the smooth stream lines that existed, the mass of the orifice drops drastically and over a very short range of flow change. When this occurs, coherence of the air mass not immediately in the air stream is impossible, thus only the mass in the stream contributes to the overall mass of the orifice. Any further increase in air flow, of course, causes no change in the mass once total turbulence exists.

2. Increase of Acoustic Resistance with Air Flow.

The acoustic resistance of an orifice with air flow is composed of two quantities; namely, the usual analogous acoustic resistance R_r measured without air flow and the differential acoustic resistance R_d. Westerfelt (22) has defined the following terms in this connection as follows:

Analogous flow resistance = $R_f = \dfrac{p}{Q} = \dfrac{\rho Q}{S^2}$

Differential Resistance $R_d = \dfrac{\partial p}{\partial Q} = \dfrac{2\rho Q}{S^2} = 2R_f$

From purely energy considerations, neglecting friction, it can be shown that for direct current flow through an orifice, the difference in pressure p measured on each side is equal to

$$p = \frac{1}{2}\rho V^2 = \frac{1}{2}\frac{\rho Q^2}{S_o^2}$$

where ρ is the density of the air, Q the volume flow and S_o the area of the orifice. The plot of p versus Q is shown in Figure ~~19~~ 17 for the 0.5 centimeter and 0.35 centimeter diameter orifice, and very closely follows the parabolic relationship given. but does not check even approximately in the relative magnitude of $\frac{\Delta p}{\frac{1}{2}\rho v^2}$ which he obtains as 0.02 !!

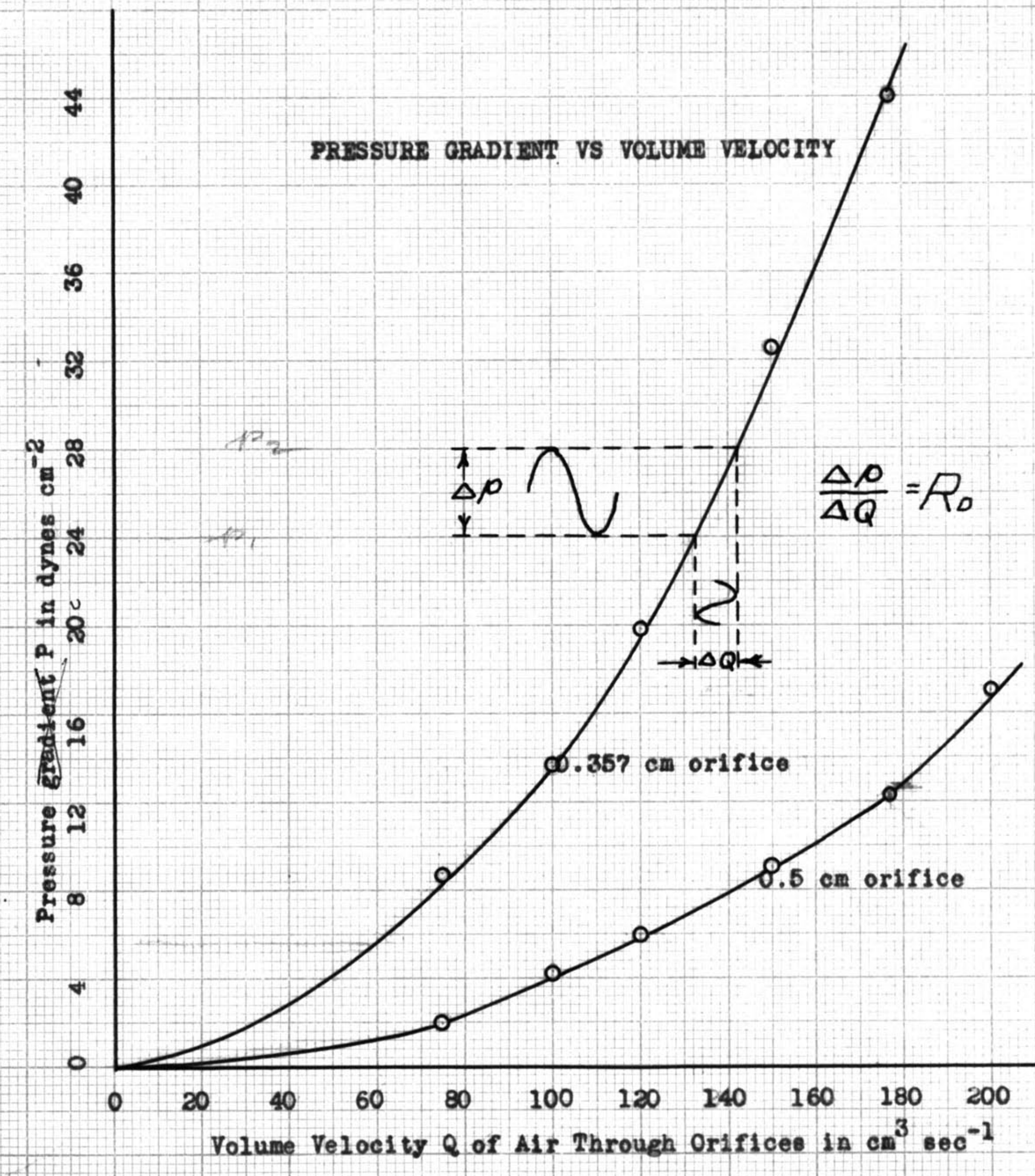

PRESSURE GRADIENT VS VOLUME VELOCITY
Pressure gradient P in dynes cm^{-2}
Volume Velocity Q of Air Through Orifices in cm^3 sec^{-1}
0.357 cm orifice
0.5 cm orifice
Δp
ΔQ
$\frac{\Delta p}{\Delta Q} = R_0$
0
4
8
12
16
20
24
28
32
36
40
44
20
40
60
80
100
120
140
160
180
200

FIG. 17

From the definition of analogous flow resistance, R_f, it is seen that the differential resistance R_d is simply the $\frac{\partial P}{\partial Q}$ or the slope of the P-Q curve at any point. This, then, is the value of acoustic resistance at higher rates of air flow shown by the curves in Figures 9, 10, and 11. No air flow corresponds to operating at the origin of the P-Q diagram where the flow is zero. In the region between no air flow and about 400 centimeters per second air flow the acoustic resistance is apparently a combination of the usual acoustic resistance (which varies as the first power of the frequency) and the differential acoustic resistance which is nearly constant with frequency. Although at first thought it would appear that the acoustic resistance measured with air flow is the sum of the usual analogous resistance R, and the differential acoustic impedance R_d, extrapolation of the rectilinear resistance passes through the origin instead of having a constant value at no air flow. The fact that this extrapolation passes so close to the origin indicates that the dissapation of sound energy is almost entirely a change from potential energy to kinetic energy and that the effects of friction or heat losses may be neglected.! (Turbulence absorbs kinetic energy)

3. <u>Correlation between HIgh Level Sound and Air Flow</u>

The impedance of an orifice undergoes a similar change as the alternating particle velocity through the orifice is increased by increasing the intensity of the sound. Ingård has studied this in considerable detail. He has found that with very high levels of sound, the usual laminar flow breaks down into turbulence in several stages and ultimately becomes a series of pulses being emitted from each side of the orifice. A similar explanation has been given regarding the change in mass, but judging from the plot of high sound pressure levels, the mass change would appear to be somewhat greater than for the case with air flow. This may result from the jet existing on both sides of the orifice with laminar flow being impossible, whereas, with air flow, the upstream condition should be modified only slightly by air flow. Figure 13 has plotted on it the values of the acoustic impedance of an orifice measured for high level sound, which shows the similar effects occuring with high level sound and with air flow.

B. Shift in Frequency and Lowering of Q of a Resonator With Air Flow

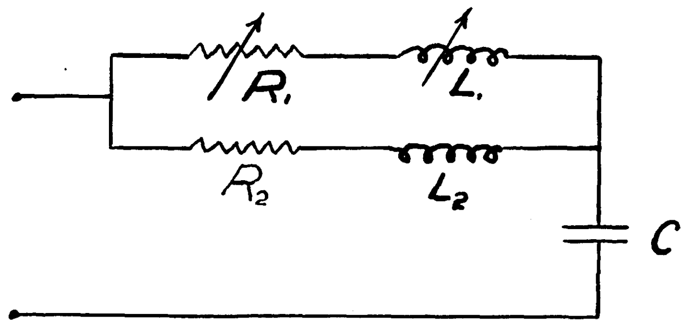
The shift in frequency of the resonance peak with air flow is not as great as the computed value. This may be explained by recalling that the acoustic resistance without air flow is a function of frequency, becoming greater with increasing frequency. The result of this phenomena is that the peak of the resonance curve is at a higher frequency than the resonance frequency.

The differential acoustic resistance, R_d, that acoustic resistance measured with considerable air flow, is not a function of frequency, and for the high Q resonance curve, the resonance frequency will occur at the center of the peak. This means that the observed shift in the peak of the resonance curve is less than the actual shift of the resonance frequency.

The usual definition of Q as used in electrical terminology is the resonant frequency divided by the band width determined by the half power points. For the sake of simplicity, Q as used in connection with the acoustic resonance curves, is defined as the peak frequency divided by the band width determined by the half power points. Since the resonant frequency for acoustic elements for no air flow is slightly below the peak, there is some distinction between the two definitions even for a high Q curve.

The computed Q of a combination of the two orifices undergoing mass and resistance change is rather meaningless without knowing the value of the acoustic resistance as a function of both frequency and air flow when it is composed of both types of resistance. This, of course, is the region where the resistance is changing from the linear range to the differential resistance R_d range. Nearly all the resonance curves measured are in this range.

A resonator composed of two orifices, only one of which undergoes impedance change with air flow may be explained by the following electrical circuit analogy:



With R_2 and L_2 fixed in value, one may vary the resistance of R_1 and the inductance L_1 in a manner similar to that which occurs for the acoustic elements with air flow. That means that R_1 is increased slightly as L_1 is decreased to half its original value. This results in a raising in the resonant frequency and a lowering of the Q. Further increase of air flow corresponds to increasing the value of R_1, while keeping L_1 constant. As R_1 is increased many times over its original value, the branch containing R_1 and L_1 is effectively open circuited. This results in the frequency of the resonance peak shifting down to the value determined by the circuit containing L_2 and C only. The Q of the circuit likewise would then be determined by the value of R_2. This is exactly what occurs for the acoustic resonator composed of two orifices and a cavity, when only one orifice is effected by air flow.

C. Changes in Acoustic Mass and Resistance with Air Flow Past the Orifice.

The acoustic mass and resistance of an orifice undergoes a similar change with air flow past the orifice instead of through it. Although, it was impossible to measure this change by the precision impedance tube, the use of a side branch resonator gave resonance curves quite similar to the resonator withflow through the orifice. The mechanism by which the resistance and the mass changes occur are probably quite similar to those which cause the changes of mass and resistance with flow through the orifice. Destruction of the smooth flow lines by turbulence would decrease the mass in a manner quite analogous to the explanation given for air flow through the orifice.

V CONCLUSIONS

Air flow of comparatively low velocity through or past an orifice will cause the acoustic mass of the orifice to decrease to less than half its original value. When turbulence causes destruction of the laminar flow pattern, the mass decreases and remains at a constant value with apparently no further change for greater velocities of air flow.

Air flow causes the acoustic resistance to change from the usual analagous acoustic resistance varying with frequency to a differential resistance independent of frequency, but increasing with air flow. In the transition period the acoustic resistance is a combination of the two types.

The conduction of sound through an orifice, as a result of the decrease in the acoustic mass will be enhanced by slow air flow through or past the orifice. Higher air flow results in an increase in the magnitude of the impedance because of the rapid rise in acoustic resistance for small orifices.

APPENDIX

Notes on Measurement of Acoustic Impedance by the Precision Impedance Tube.

The theoretical aspects of measuring acoustic impedance by the precision impedance tube are described by Morse and Beranek. Certain practical aspects of measuring acoustic impedance of an orifice with air flow complicate the problem somewhat, and in general reduce the precision of the equipment.

The scatter of points of the acoustic reactance curve at high rates of air flow indicates that in this region the precision of the results is least. Two reasons for this lack of precision are apparent. First, the mapping of the complex hyperbolic tangent on the U-V plane is such that a slight error in the determination of the imaginary part results in considerable error in acoustic reactance although, the resistance values will be determined with considerable precision. Second, since the imaginary part of the complex hyperbolic tangent is determined from a measurement of the distance of the pressure minimums from the orifice, the degree of accuracy can be no greater than the accuracy with which the points of minimum sound pressure can be determined.

The procedure used in locating these points of minimum sound pressure ordinarily gives good results but for high air flow the same procedure leads to considerable error. For no absorption of sound the points of minimum pressure are sharp, but as the absorption increases with air flow, the minimum broadens. The procedure usually used involves locating the minimum sound pressure level and then locating the points each side of the minimum.which are three or four decibels above the minimum. The mid point between the two 3-decibel points is then taken as the location of the minimum. This method eliminates the difficulties resulting from the broadening of the pressure minimum and further gives a strong signal to measure which will be less effected by noise. The accuracy of this method is adversely affected when air is rushing through the orifice. Slight changes in the rate of air flow, and the random fluctuation usually associated with turbulence, results in a lowering and raising of the minimum pressure points in the space of a short interval. Any lowering or raising of the minimum which occurs because the velocity of air flow changes slightly results in considerable shift in the location of the 3 decibel points. In addition the noise created by air flow further complicates making accurate measurements. These reasons combine to give poor results of reactance measurements at high flow rates.

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